A systems approach to quantum computation

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Experiment: J. Petta, A. C. Johnson, E. A. Laird, A. Yacoby[2], C. M. Marcus

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References: [Petta *et al*. Science (2005), Taylor *et al*. Nature Physics (2005)]

In this talk:

- Fault-tolerance requirements
- Qubit choice and operations
- Non-local coupling
- Architecture

Fault-tolerance requirements

Fault-tolerant quantum computation

Assume:

- perfect quantum memory
- distance-independent 2-qubit gates
- fast accurate analog classical control circuitry
- operational errors *only*, with probability p

Threshold theorem(s):

- arbitrary computation possible for $p < p_{\text{thres}}$

The system-level requirements determine
the qubit-level properties

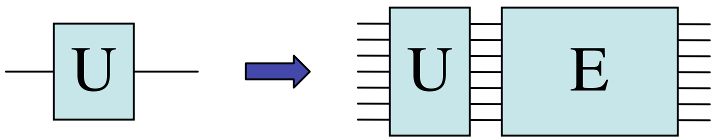
e.g., gates, memory, transport

The qubit-level properties determine
the system-level requirements

e.g., choice of code, concatenation, etc.

Quantum error correction

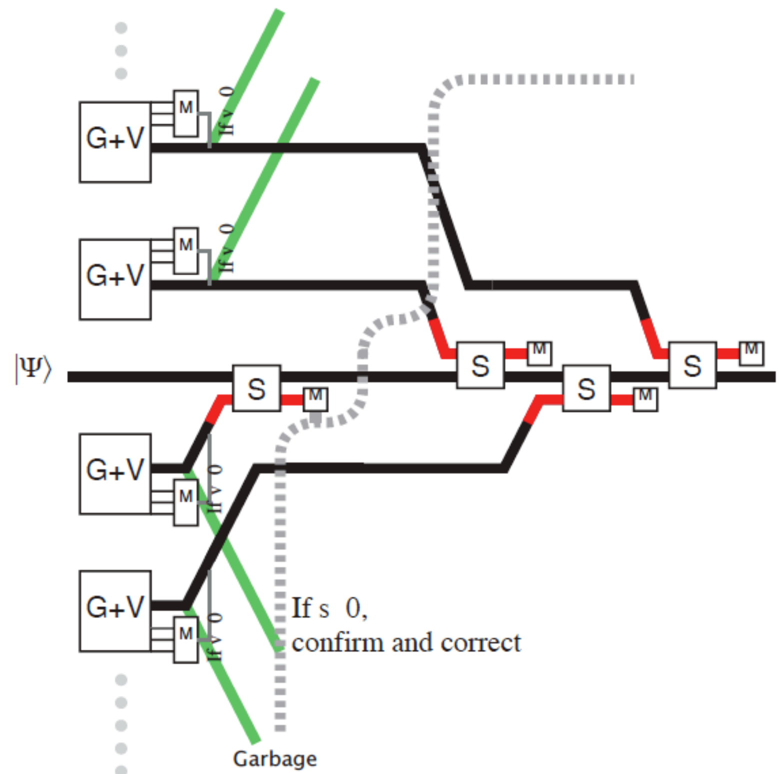
- Replace physical qubits / gates with encoded qubits / gates



For single error correcting/ detecting codes:

$$p' \sim n_{(\text{gates in } U+E)}\, p^2$$

- Requires: parallelism, memory ancillary qubits, efficient entropy extraction
- In practice: transport overhead, autonomous control



Alternative approaches?

- Cluster state computation [Raussendorf & Briegel 2001]
  - prepare highly entangled state
  - selective, sequential measurements
  - fault tolerance possible [Leung 2005]

- Hamiltonian-based computation
  - topological codes [Kitaev 1997]
  - adiabatic computation [Farhi 2000]

Different systems requirements!

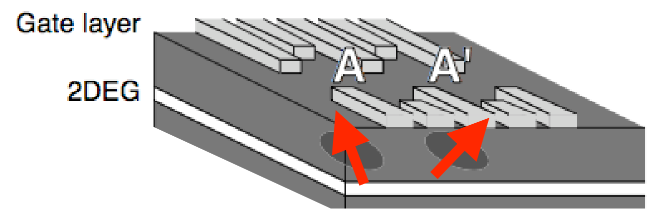
Qubit choice and operations

How to choose a favorite poison

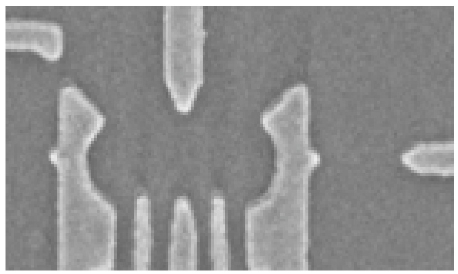
- Identify requirements
  - For gates:
    - What is fast?
    - What is error prone?
    - What is "hard"? (can we find a laser / pulse generator / material…)
  - For memory, transport:
    - Do we need "deep" storage? (I.e., combine optical qubit during logic with hyperfine states during waiting / transport)
    - Are we sensitive to other mechanisms in transport? How long will it take?
  - For alternative schemes:
    - What gives strong inter-qubit coupling? What builds quantum mechanically interesting states?
- Choose an appropriate coding scheme

Example: spin in quantum dots

- Qubit: single electron spin in a quantum dot
  [Loss & DiVincenzo, PRA (1998), Imamoglu *et al*. PRL (1999)]
- Interactions: coulomb / exchange + local gate control + local magnetic field control



– Over the past few years (in GaAs)
  Control electron number from 0, 1, 2 . . .
  [Sachrada *et al*. PRL (2002)]
  Single-charge measurement using SET or QPC
  [Devoret *et al*. Nature (2000), DiCarlo *et al*. PRL (2003)]
  Spin state preparation / measurement
  Long T_1 time at 4.0 Tesla (> ms observed)
  [Hanson *et al*. PRL (2003), Elzerman *et al*. Nature (2004), Golovach, PRL (2004)]



– Missing: coherent spin rotations by, e.g., ESR
  Why? Dominant *phase* noise term: hyperfine (nuclei)
  High power, low frequency noise
  [Merkulov *et al*. PRB (2002), Khaetskii *et al*. PRL (2002)]

$T_2^* \sim 10$ ns

Memory requirement:
Dynamical decoherence free subspace

$$\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle, \left|\uparrow\downarrow\right\rangle + \left|\downarrow\uparrow\right\rangle$$

[Zanardi PRA (2000), Taylor *et al.* PRL (2005)]

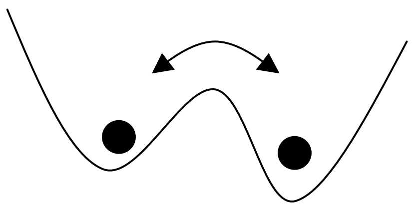
- Dephasing: $\alpha\left|\uparrow\downarrow\right\rangle + \beta\left|\downarrow\uparrow\right\rangle \rightarrow \alpha\left|\uparrow\downarrow\right\rangle + e^{i\phi}\beta\left|\downarrow\uparrow\right\rangle$
- Exchange gate produces SWAP

$$\alpha\left|\downarrow\uparrow\right\rangle + e^{i\phi}\beta\left|\uparrow\downarrow\right\rangle$$
$$e^{i\phi}\alpha\left|\downarrow\uparrow\right\rangle + e^{i\phi}\beta\left|\uparrow\downarrow\right\rangle$$
$$e^{i\phi}(\alpha\left|\uparrow\downarrow\right\rangle + \beta\left|\downarrow\uparrow\right\rangle)$$

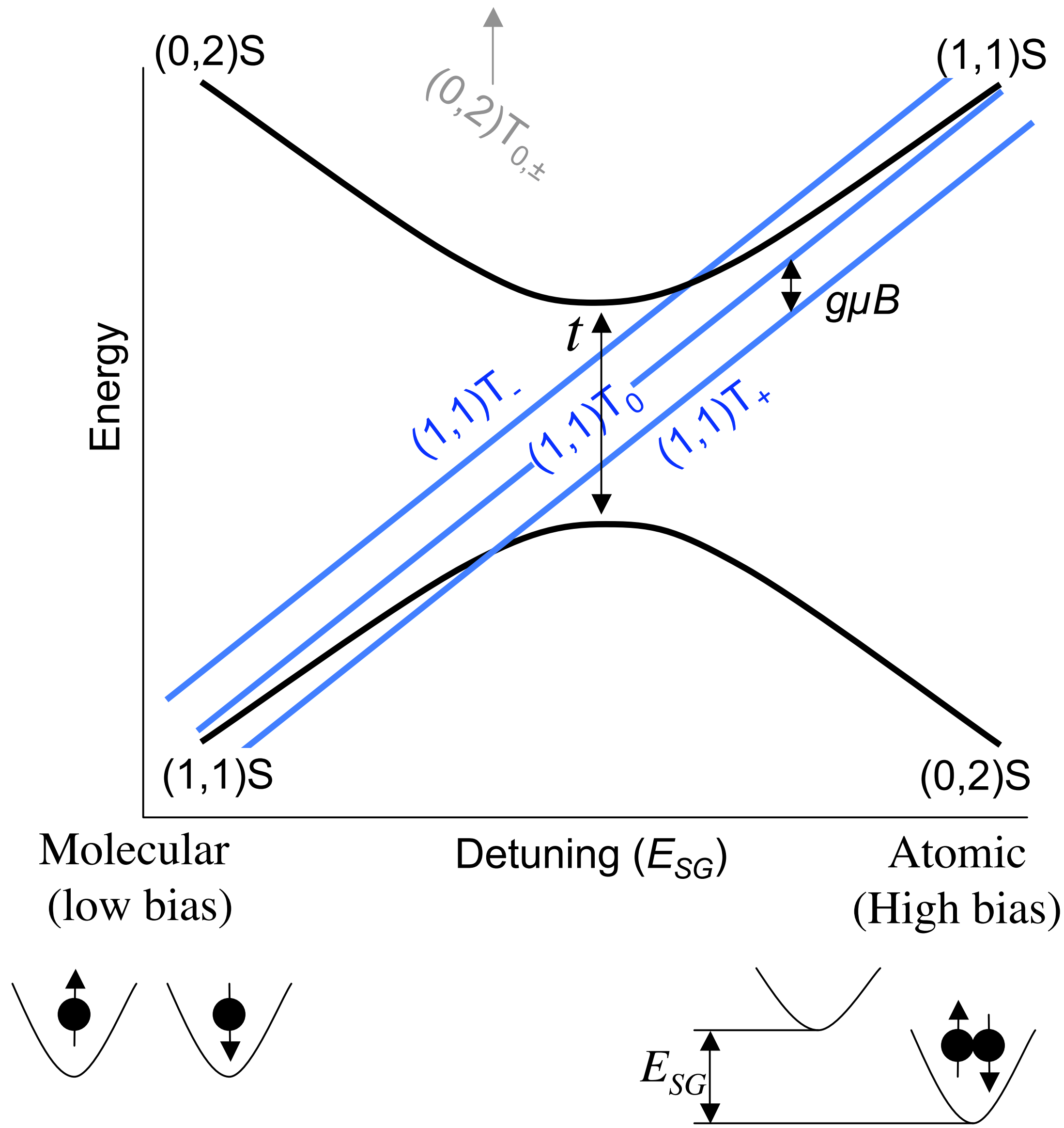
- Protect against dephasing by repeated SWAP operations (a la NMR refocusing sequences). A good memory!
  – can we do logical computation in this space?
  – is local, autonomous control an option?

Autonomous, fast gates:
operations with *intrinsic* interactions

- Double quantum dot

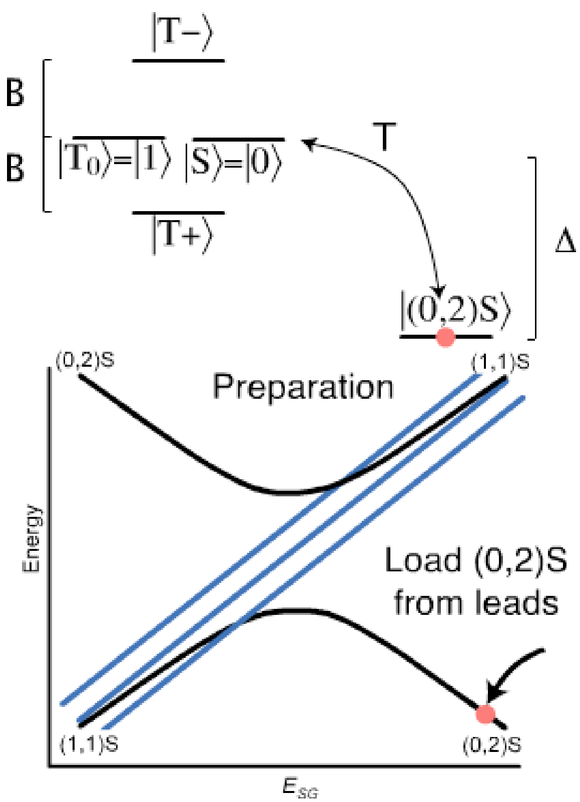


- Singlet and triplet
  - Molecular: (1,1)
    - Weak tunnel coupling (no exchange)
  - Atomic: (0,2)
    - Exchange splits singlet and triplet
  - Change bias for transition



Working within the DFS

- Load from leads to produce a singlet: kT < J
- “Rapid adiabatic” transfer to (1,1) produces logical zero



[Levy PRL (2002), Wu & Lidar PRL (2002), Mohseni & Lidar PRL (2005)]

Working within the DFS

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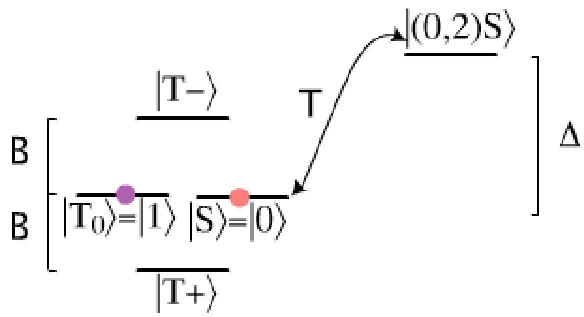
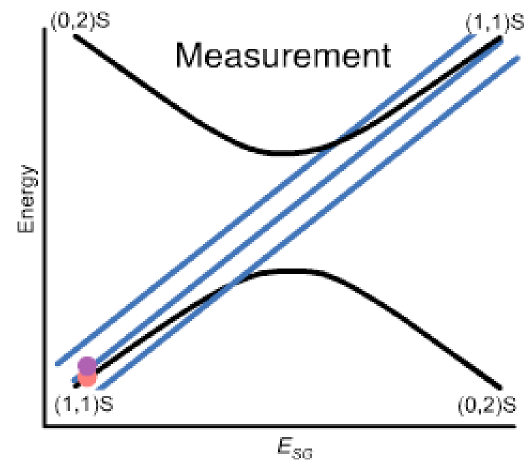
- Reverse: spin-to-charge conversion





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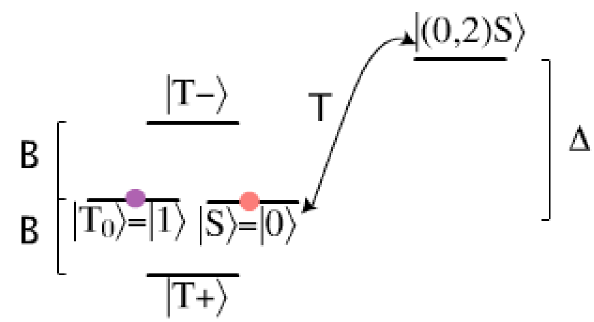

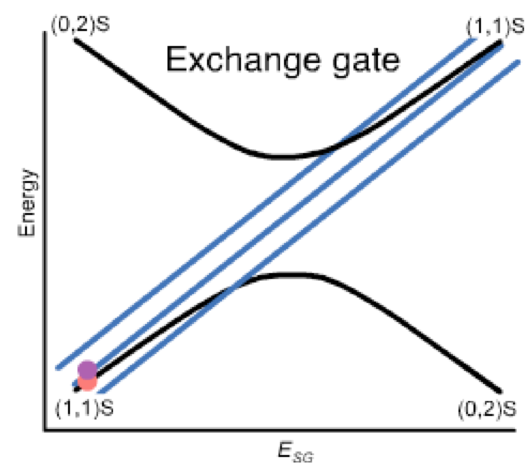

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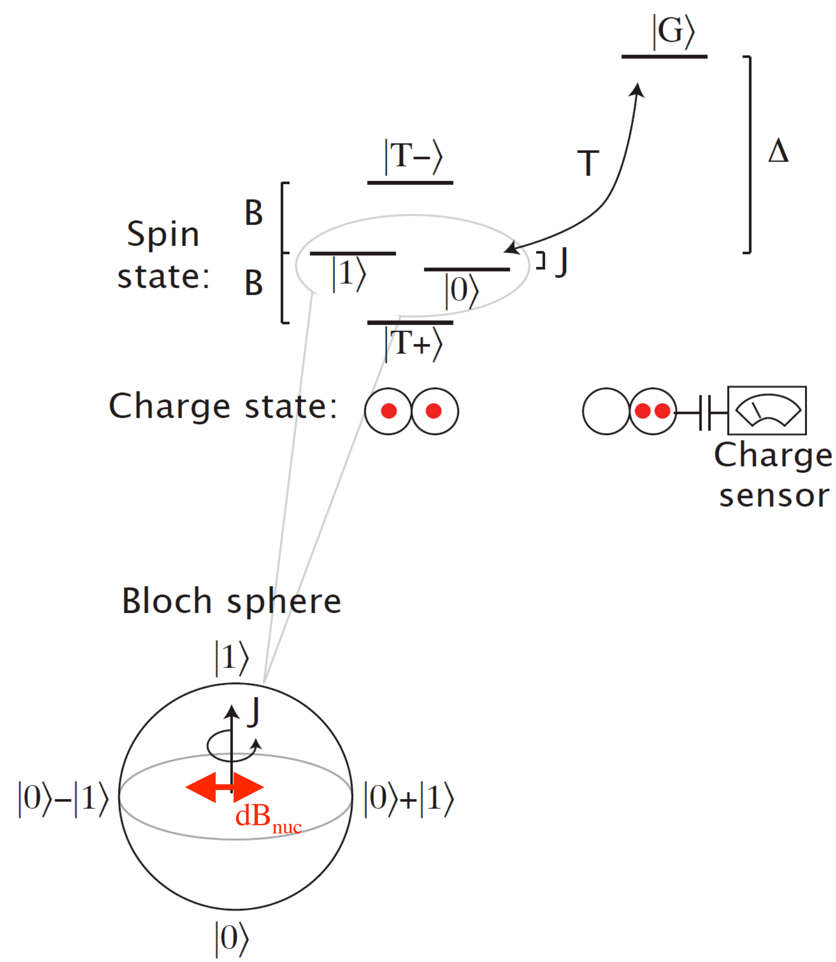
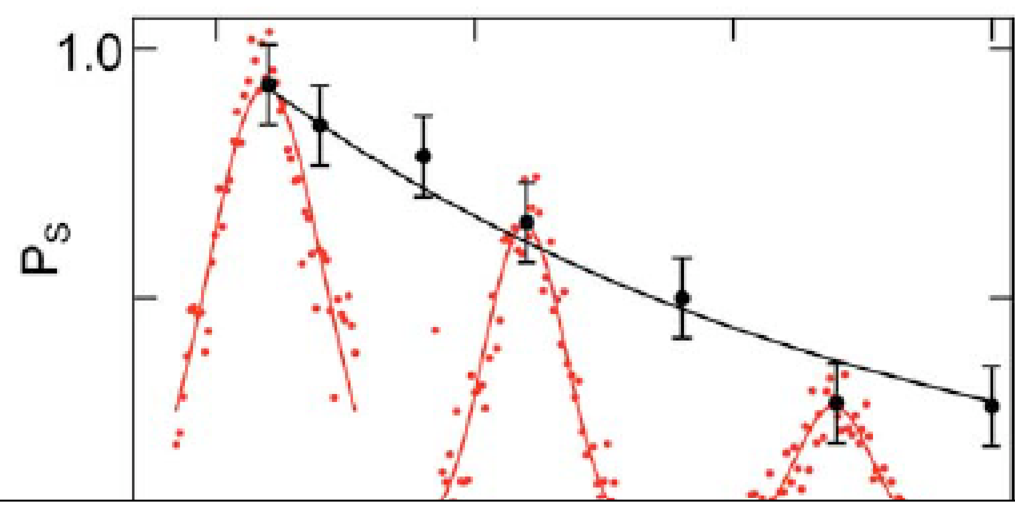
Working within the DFS

- Load from leads to produce a singlet: kT < J
- "Rapid adiabatic" transfer to (1,1) produces logical zero
- Reverse: spin-to-charge conversion
- Exchange gates for Z rotations
- SWAP to protect against nuclei. *Dynamical* DFS

[Levy PRL (2002), Wu & Lidar PRL (2002), Mohseni & Lidar PRL (2005)]



Dynamical decoherence free subspace: experiment



A better qubit

$T_2 > 100\ T_2^* > 10^3$ gate operations

likely limit: electron-mediated nuclear flops

J. R. Petta, A. C. Johnson, J. M. Taylor, E. A. Laird,
A. Yacoby, M. Lukin, C. Marcus Science (2005)

Improving operations: feedback with slow measurement

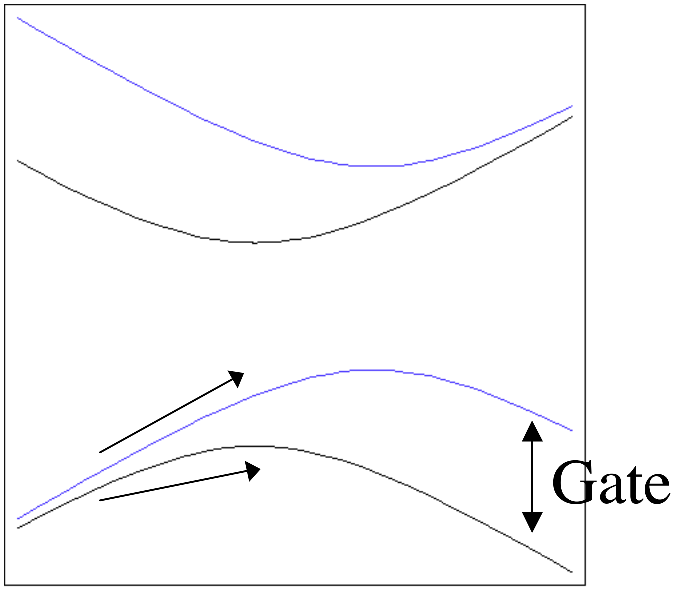
- Can we measure the nuclear field?
  - Ramsey: $\pi/2$ pulse, wait, $\pi/2$ pulse, measure, repeat
    - Double-dot case: separate, wait, measure, repeat
    - Slow part: measurement!

- Feedback: use result to change
  phase / estimate of frequency of future operations

Improving quantum operations

- Feedback
  corrects low frequency noise

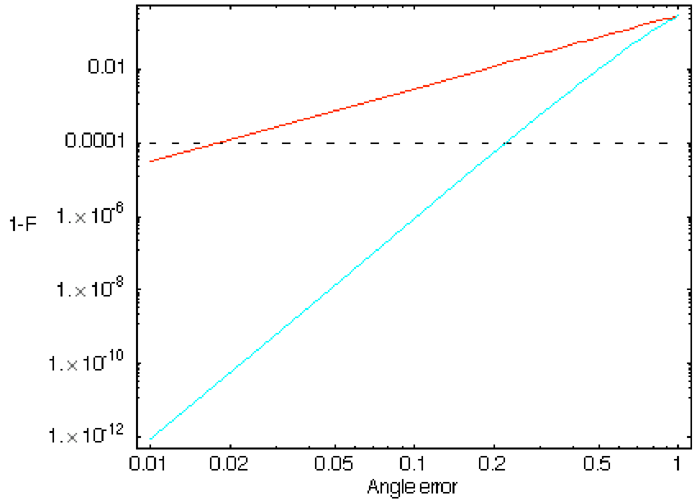
- Low-noise operating point
  "quantum transistor"
  see superconducting qubits



- Composite pulses
  removes low frequency noise

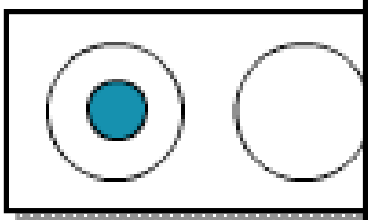
$$R_{x,\mathrm{BB1}}^{\pi/2} = UR_Z^{-\phi}U^4R_Z^{-2\phi}U^8R_Z^{2\varphi}U^4R_Z^{\phi}U$$

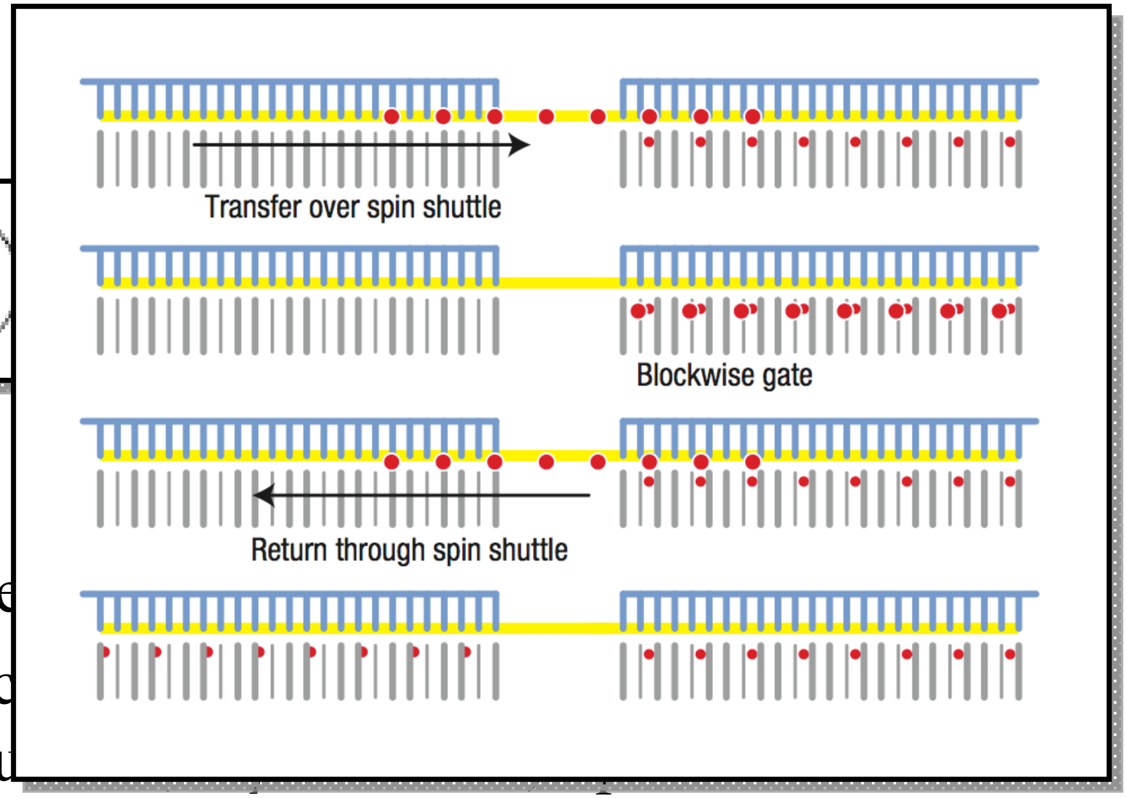
[Van der Sypen & Chuang, RMP 2004]



Non-local coupling

Non-local coupling:
A (qubit) shuttle

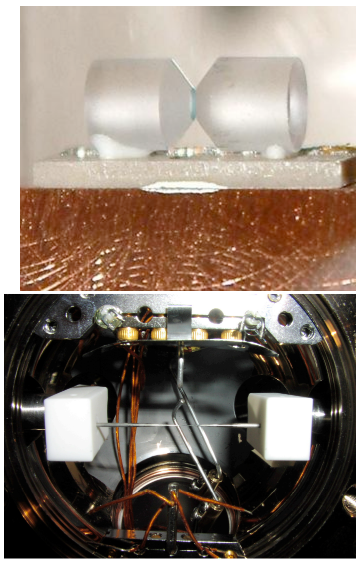




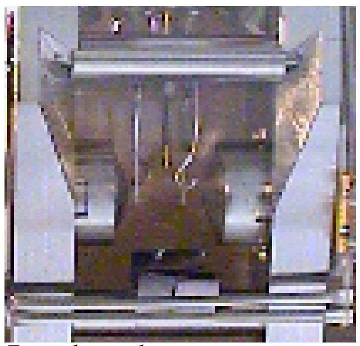
- A CCD or a se
- Fast: adiabatic
  satisfied for su
- Can be highly parallel

Non-local coupling: “Flying” qubits

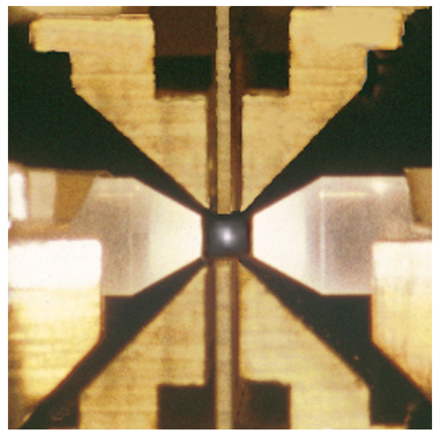
- Example: cavity QED (optical, μwave resonator)
  long distance, but not parallel



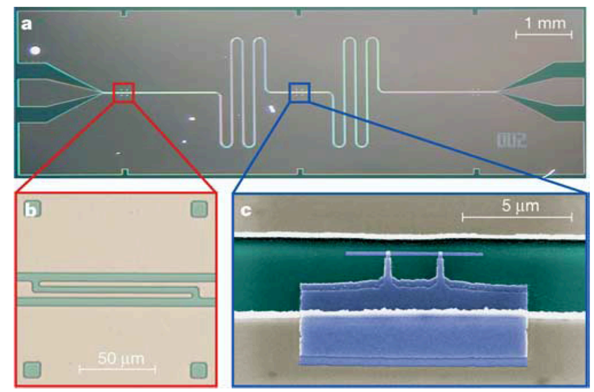
Georgia Tech / U Mich



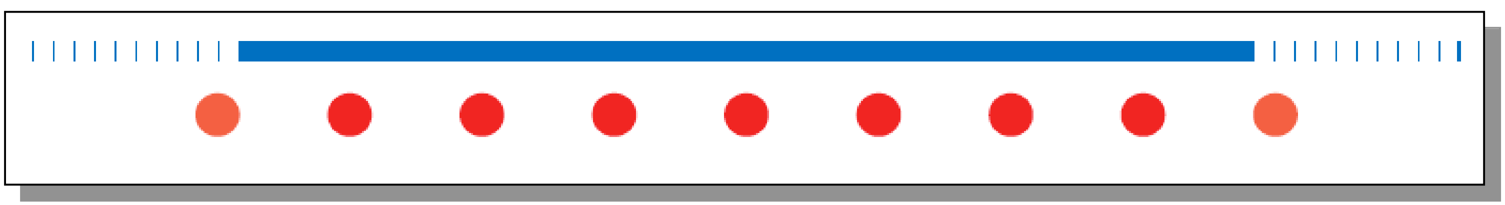
Innsbruck



Sussex

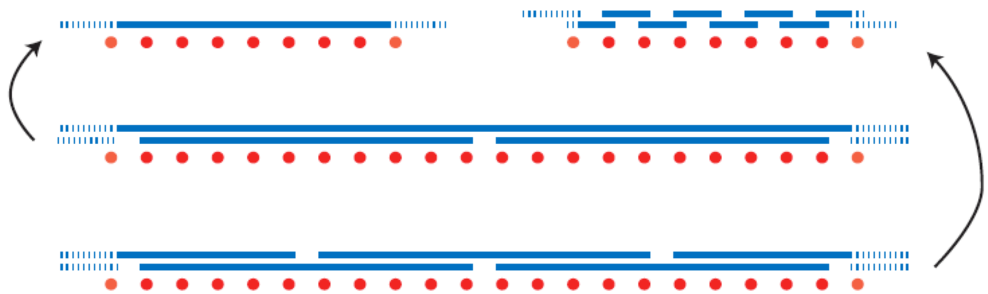


Yale



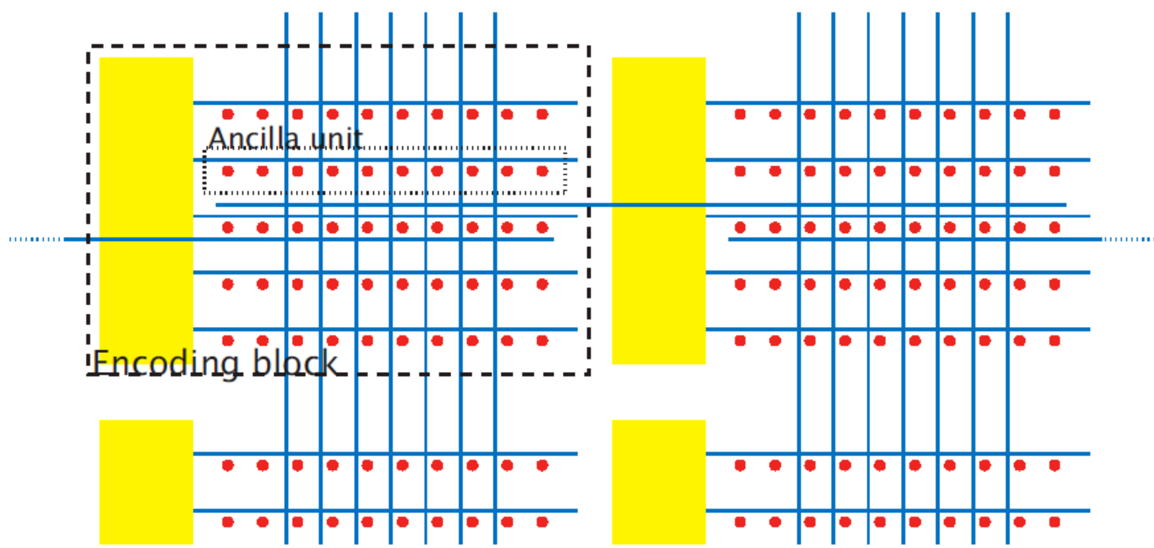
Non-local coupling: “Flying” qubits

- How to scale? Limited gate bandwidth in any given bus… choice of replacement rules

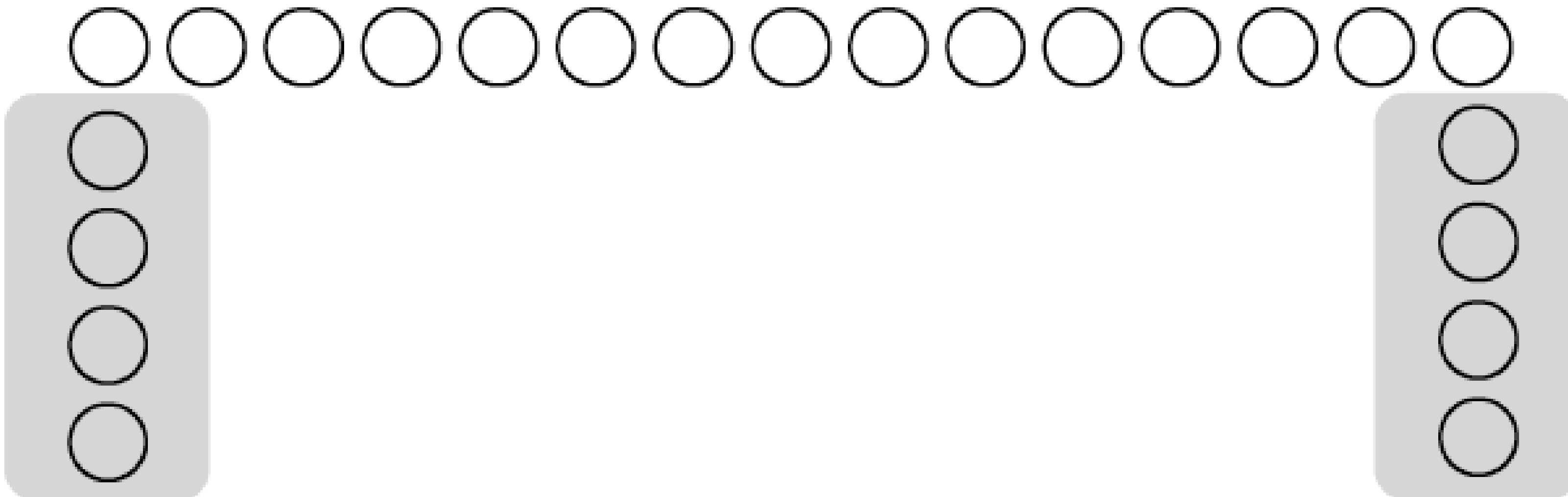


- What does it “look” like?

- Or, composite scheme



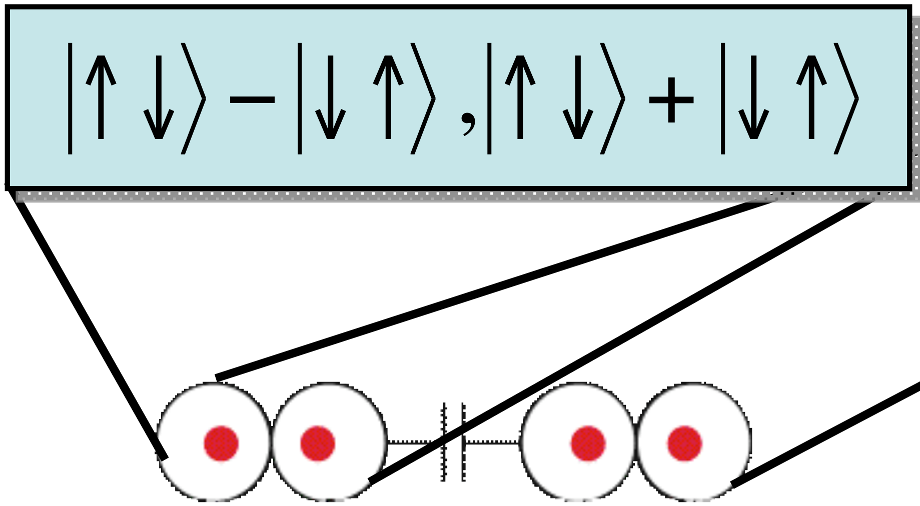
Preparing long-distance entanglement through shuttling with DFS

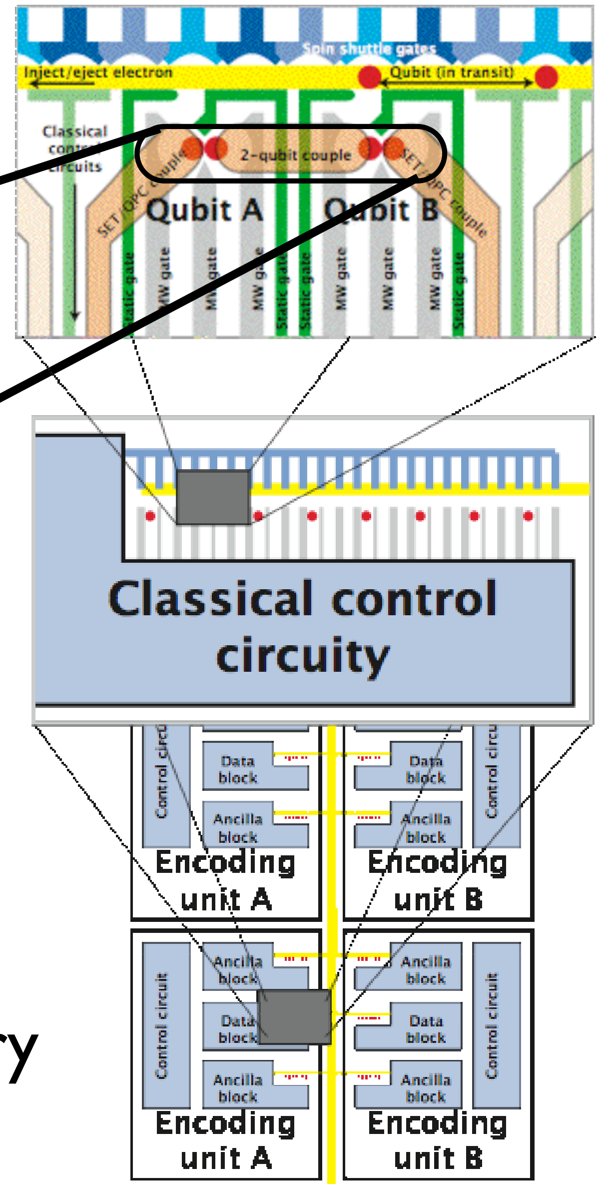


- Use generation of entangled singlet pairs of qubits: exchange only approach feasible
- Adiabatically pump charge (qubits) through a series of potential wells
  - Averages over fluctuating fields
  - Work entirely in singlet-triplet dynamical DFS to further reduce errors
- Local operations purify fidelity of final pair (and remove leakage)
- Teleportation-based non-local gates implemented with purified pair
- Bandwidth “on-demand”

Architecture

A shuttle-based architecture



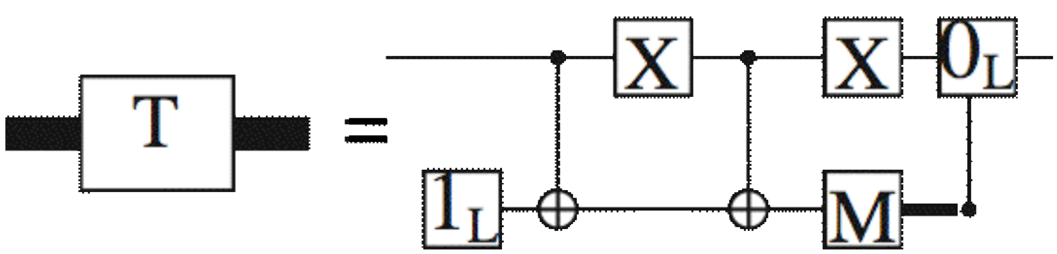


- Recall: all operations controlled by
  - electrical gates
  - timing
- Measurements also charge based
- Make modular, autonomous circuitry

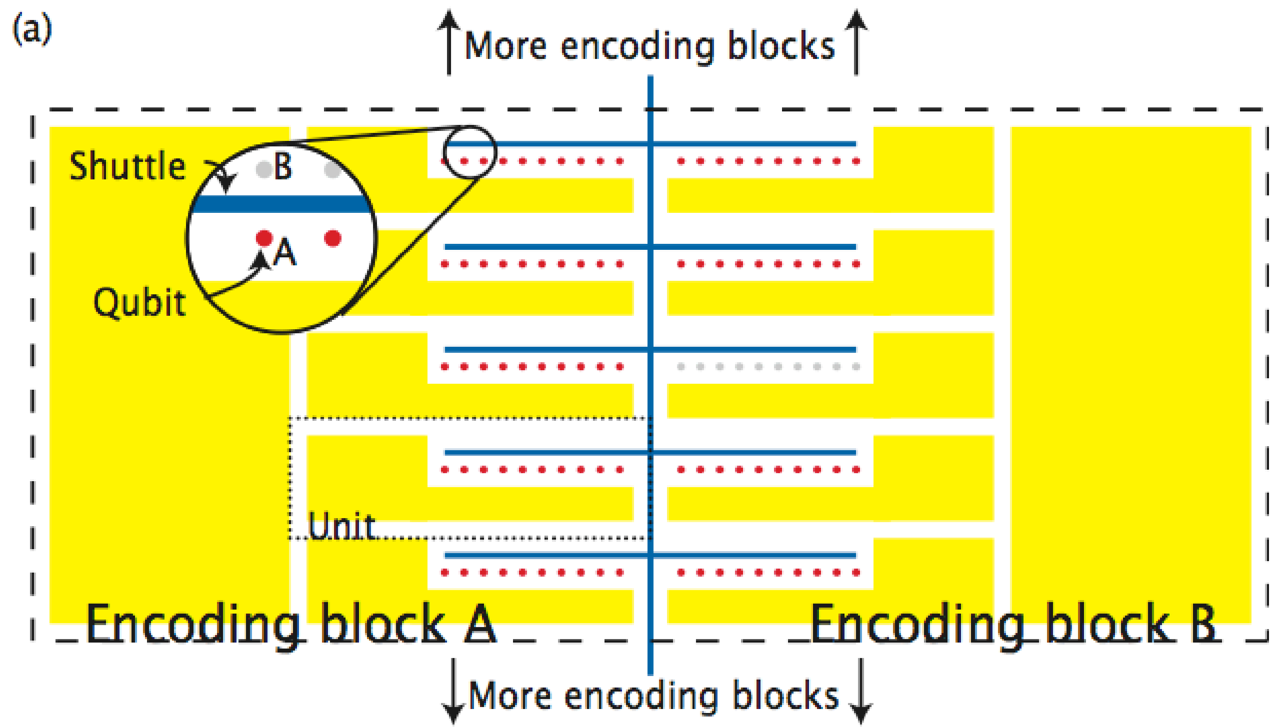
[Copsey *et al*. SPAA (2003), Taylor *et al*. Nature Physics (2005)]

Example: leakage error detection

- Recall: 2-qubit gate is singlet-triplet dependent;
  - $T_0, T_\pm$ operate the same way
- But, X rotations only switch S, T_0 ($T_\pm$ untouched)
- Idea: use ancillary qubit to check X rotations with 2-qubit gates
  - Logical subspace untouched, ancilla result 0
  - $T_\pm$ states give result 1, replace with logical 0



Error correction in the architecture

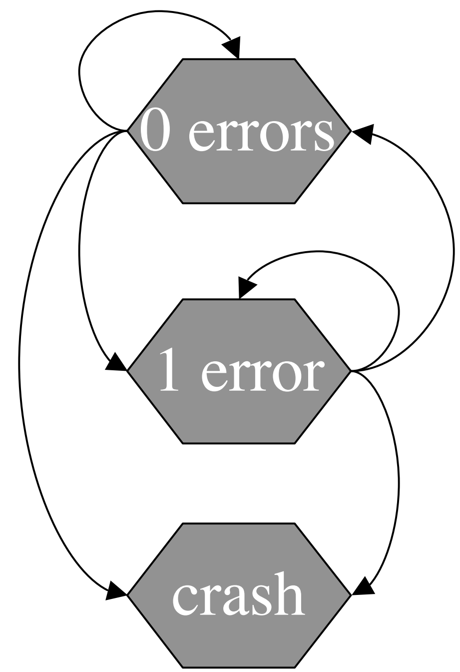


A threshold calculation

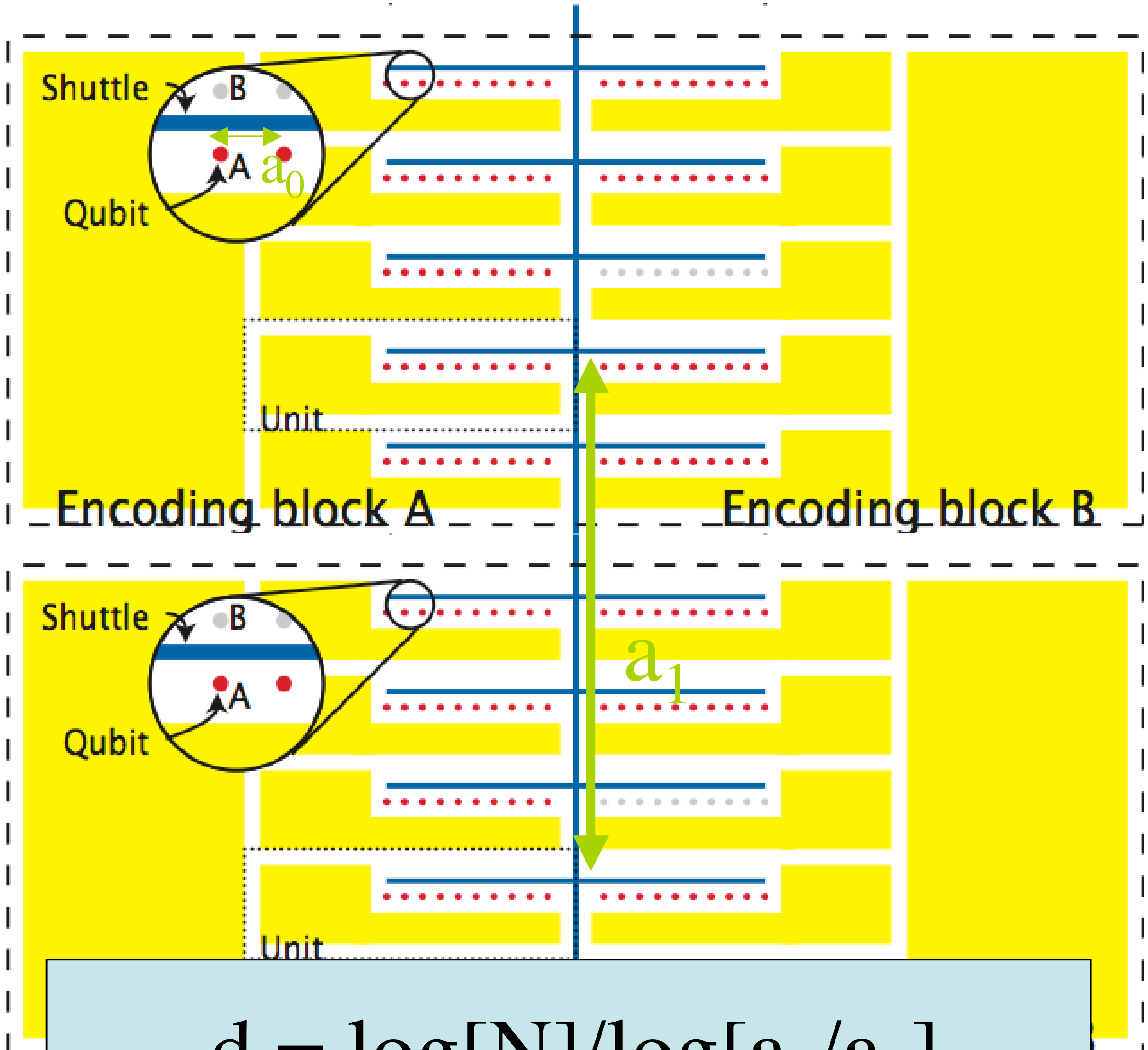
Eight "locations" to replace recursively

	error prob	memory err prob
1-qubit unitaries	p_1	m_1
2-qubit unitaries	p_2	m_2
Measurement of single spin	p_3	m_3
Shuttle one qubit l quantum dots	lp_4	lm_4

- Consider error model for each level of recursion: p1-p4, m1-m4
- Find a map from previous level to next level (increasing distance, increasing memory time)
- Overestimate: some benign errors counted as crashes

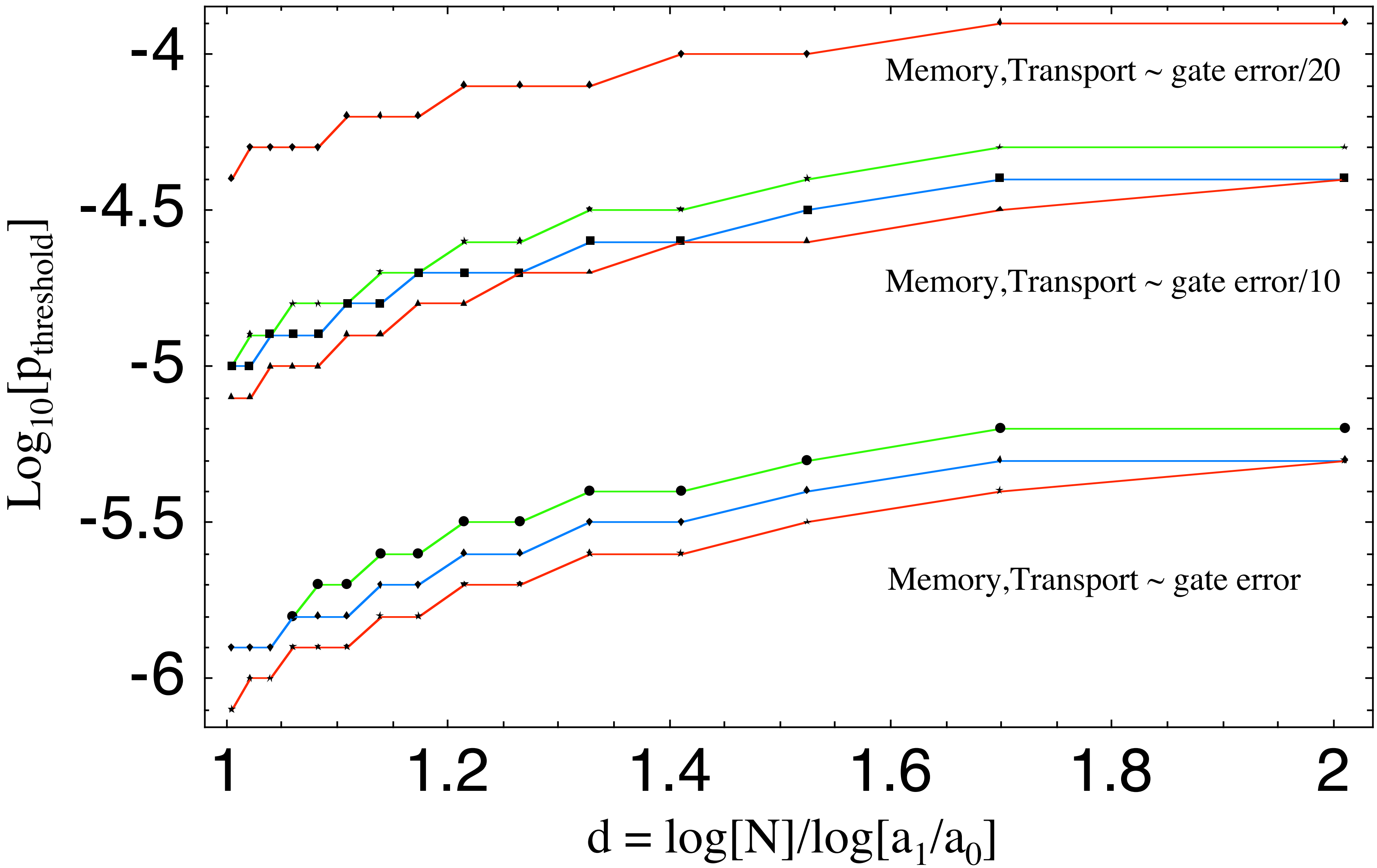


Dimensionality



$$d = \log[N]/\log[a_1/a_0]$$

Scaling as a function of dimension



Outlook

- Systems requirements => qubit choices
  - Use fundamental resources: e.g., charge control, static magnetic fields, exchange interaction
  - feedback, noise-free points, composite pulses

- Long-range coupling mechanisms
  - Shuttling (local parallelism “for free”)
  - Photons (parallelism difficulties)

- Architecture
  - Dimensionality plays important role for finite memory / transport